UNIVERSITI TEKNIKAL MALAYSIA MELAKA

**Faculty of Electrical Engineering**

# SINGLE INPUT FUZZY LOGIC CONTROLLER FOR YAW CONTROL OF UNDERWATER REMOTELY OPERATED CRAWLER

**Muhammad Iktisyam bin Mohd Zainal**

**Master of Science in Mechatronic Engineering**

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# SINGLE INPUT FUZZY LOGIC CONTROLLER FOR YAW CONTROL OF UNDERWATER REMOTELY OPERATED CRAWLER

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**A thesis submitted**
**in fulfillment of the requirements for the degree of Master of Science in Mechatronic Engineering**

**Faculty of Electrical Engineering**

**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

**2018**

## DECLARATION

I declare that this thesis entitled "Single Input Fuzzy Logic Controller for Yaw Control of Underwater Remotely Operated Crawler" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ........................................................

Name : Muhammad Iktisyam bin Mohd Zainal

Date : ........................................................

## APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechatronic Engineering.

Signature : ........................................................

Supervisor Name : Dr. Mohd Shahrieel bin Mohd Aras

Date : ........................................................

**DEDICATION**

To my beloved mother and father

**ABSTRACT**

Underwater Remotely Operated Crawler (ROC) is a class of the Unmanned Underwater Vehicle (UUV) that is tethered, unoccupied, manoeuvres on the seabed and remotely operated by a pilot from a platform. Underwater characteristic parameters such as added mass, buoyancy, hydrodynamic forces, underwater currents, including pressure could considerably affect and reduce the mobility of the ROC. The challenges faced by the ROCs are that the needs to reduce the overshoot in the system response, including, the time response and settling time. For yaw control (a motion around the *z-axis*), an occurrence of an overshoot in the system response is highly intolerable. Reducing the overshoot in the ROC trajectory is crucial since there are many challenging underwater natures and underwater vehicle control problems while studies on finding the solutions are still ongoing to find an improvement. Conventional Proportional-Integral-Derivative (PID) controller is not robust to be applied in the ROC due to the non-linear dynamic model of the ROC and underwater conditions. Besides that, by reducing the overshoot, the ROC mobility will be much more efficient and provided a reliable platform for underwater data mining. This study is focused to give an optimum performance of yaw control without overshoot in the system response and faster time response. This research begins by designing an underwater ROC as the research's platform. Then, the designed ROC is simulated by using SolidWorks software obtain the analysis of structural integrity and hydrodynamic properties. System identification technique is conducted to obtain the empirical modelling design of the fabricated ROC which equipped with Inertial Measurement Unit (IMU) sensor. The fuzzy logic controller (FLC) is designed based on 5 by 5 rule matrix which has to deal with fuzzification, rule base, inference mechanism and defuzzification operations. A simplification of the FLC is proposed and the method is called Single Input Fuzzy Logic Controller (SIFLC). The simplification is achieved by applying the "signed distance method" where the SIFLC reduces the two-input FLC to a single input FLC. In other words, SIFLC is based on the signed distance method which eventually reduces the controller as single input-single output (SISO) controller. A PID controller is designed for the purpose of benchmarking with the FLC and SIFLC. SIFLC has the capability to adapt the non-linear underwater parameters (currents, waves and etc.). This research has discussed and compared the performance of PID, FLC and SIFLC. The algorithm is verified in MATLAB/Simulink software. Based on the results, SIFLC provides more robust and reliable control system. Based on the computation results, SIFLC reduces the percentage of overshoot (%OS) of the system and achieve 0.121%, while other controllers (PID and FLC) 4.4% and 1.7% respectively. Even that so, this does not mean that PID and FLC are not reliable but due to the presence of %OS.

# *ABSTRAK*

*Perangkak Kawalan Jauh (ROC) merupakan satu kelas Kenderaan Dasar Laut Tanpa Pemandu (UUV) yang terikat dengan kabel, tanpa pemandu, beroperasi di dasar laut dan dikawal oleh seseorang dari platform permukaan. Ciri dalam air seperti penambahan jisim, daya apung, daya hidrodinamik, arus dasar laut serta tekanan boleh menjejaskan dan membataskan pergerakan ROC. Cabaran dihadapi ROC adalah keperluan mengurangkan peratusan terlajak dalam tindak balas sistem kawalan termasuk masa tindak balas dan masa penetapan. Untuk kawalan rewang (pergerakkan sekitar paksi z), tindak balas lajak adalah sangat tidak boleh diterima. Mengurangkan lanjakkan dalam trajektori ROC adalah penting kerana terdapat banyak cabaran dalam masalah kawalan kenderaan bawah air dan penyelidikan kepeda mencari penyelesaian masih lagi dijalankan. Sistem kawalan Terbitan-Berkadar-Terus (PID) tidak dapat digunakan kepada ROC disebabkan model ROC tidak berkadar terus serta keaadaan dasar laut. Selain itu, dengan mengurangkan lajakkan, pergerakan ROC akan menjadi lebih cekap dan menyediakan sebuah platform yang boleh dipercayai untuk pengumpulan data dia bawah air. Kajian in memfokuskan untuk menghasilkan keupayaan yang optima tanpa lajakan dalam tindak balas system dan tindak balas masa yang cepat. Kajian ini dimulakan dengan mereka perangkak dalam air kawalan jauh sebagai barang kajaian. Kemudian, rekaan ROC disimulasikan menggunakan perisian SolidWorks untuk mendapatkan analisa struktur dan ciri hidrodinamik. Teknik pengenalan system digunakan untuk mendapatkan model empirikal ROC yang dilengkapi dengan sensor IMU. Pengawal Logik Samar (FLC) direka berdasarkan matrik 5 kali 5 yang memerlukan proses pengkaburan, dasar syarat, mekanisma kesimpulan dan pengkaburan. Pengawal pintar satu input diperkenalkan dan kaedah ini dipanggil Satu Input Pengawal Logik Samar (SIFLC). Pemudahan dihasilkan dengan menggunakan kaedah jarak ditandakan iaitu SIFLC mengurangkan dua input FLC kepada satu input FLC. Dalam kata lain, SIFLC ialah berdasarkan kaedah jarak ditandakan yang akhirnya mengurangkan input pengawal iaitu Satu Input Satu pengeluaran. Pengawal PID dihasilkan bagi tujuan penanda aras kepada FLC dan SIFLC. SIFLC berupaya untuk menyesuaikan parameter tidak berkadar terus (arus, ombak dan sebagainya. Kajian ini membincangkan dan membandingkan keupayaan PID, FLC dan SIFLC. Algoritma ini disahakan menggunakan perisian MATLAB/Simulink. Berdasarkan keputusan simulasi, SIFLC mengurangkan peratusan lajakan (%OS) system dan mencapai 0.121% manakan (PID dan FLC) masing-masing 4.4% dan 1.7%. Namun demikian, ini tidak bermakna PID dan FLC tidak dapat diharapkan kerana kewujudan %OS.*

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## LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| ADCP | - | Acoustic Doppler Current Profiler |
| AFLC | - | Adaptive Fuzzy Logic Controller |
| ANFIS | - | Adaptive Neuro-Fuzzy Inference Systems |
| ASFLC | - | Adaptive Simplified Fuzzy Logic Controller |
| AUV | - | Autonomous Underwater Vehicle |
| CFLC | - | Conventional Fuzzy Logic Controller |
| CFRP | - | Carbon Fibre Reinforced Plastic |
| DOF | - | Degree of Freedom |
| DVL | - | Doppler Velocity Log |
| FLC | - | Fuzzy Logic Controller |
| GDROV | - | General Detection Remotely Operated Vehicle |
| GPS | - | Global Positioning System |
| HOSM | - | Higher Order Sliding Mode |
| HOV | - | Human Occupied Vehicle |
| HROV | - | Hybrid Remotely Operated Vehicle |
| IMU | - | Inertial Measurement Unit |
| INS | - | Inertial Navigation System |
| LQG | - | Linear-Quadratic-Gaussian |
| MPC | - | Model Predictive Control |
| NL | - | Negative Large |
| NM | - | Negative Medium |
| NNPC | - | Neural Network Predictive Control |
| NS | - | Negative Small |
| PID | - | Proportional-Integral-Derivative |
| PL | - | Positive Large |
| PM | - | Positive Medium |
| PS | - | Positive Small |
| PSO | - | Particle Swarm Optimization |
| ROC | - | Remotely Operated Crawler |
| ROV | - | Remotely Operated Vehicle |
| SAR | - | Search and Rescue |
| SCF | - | Super Carbon Fibre |

**LIST OF SYMBOLS**

| | | |
|---|---|---|
| %OS | - | Percentage of overshoot |
| $\lambda$ | - | Slope of zero diagonal line |
| $\theta$ | - | Angle between vehicle heading |
| $d$ | - | Distance |
| $\dot{e}$ | - | Change of error |
| $e$ | - | Error |
| $k$ | - | Gain |
| $L_{NL}$ | - | Line of negative large |
| $L_{NM}$ | - | Line of negative medium |
| $L_{NS}$ | - | Line of negative small |
| $L_{PL}$ | - | Line of positive large |
| $L_{PM}$ | - | Line of negative medium |
| $L_{PS}$ | - | Line of negative small |
| $L_{Z}$ | - | Line of zero |
| $r$ | - | Output factor |
| $\dot{u}_0$ | - | Change of control output |

## LIST OF PUBLICATIONS

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# CHAPTER 1

# INTRODUCTION

This chapter is an introduction to the project that covers briefly about the research background. The motivation and significance of the research are also included in this chapter. Other significant contents are also being determined such as motivation, problem statements, objectives, scopes and report outlines of this research. Each stated content is explained in detail as an execution of the report outline.

## 1.1 Introduction

Ocean exploration technologies have been developed over the last few decades and capable of meeting many challenges impose during the exploration. The technologies available today includes platforms such as vessels and submersibles, observing systems and sensors, communication technologies and diving technologies (Oceanexplorer, 2014a). By having all these technologies, humans can explore the underwater environment, searching for new specimens, scientific research, oil exploration, hull inspections or even for search and rescue (SAR) operation. Discoveries that are made through ocean exploration are important to reduce the unknowns in the ocean areas. Besides that, an underwater exploration provides a high-value environmental intelligence needed to address both science and management needs. Exploration helps to ensure that ocean resources are well managed for future generations. The knowledge from underwater exploration is often the only source for basic information needed to respond appropriately in the face of deep-sea disasters (Oceanexplorer, 2014b).

Underwater vehicles are among of the technology often used in ocean exploration. This kind of technology increasingly sophisticated and more advanced than decades ago. The current technologies have removed the need for pilots to be in the vessels and dive into the deep water. This will reduce the risk taken for a man as the need for deeper and further underwater exploration. Smaller and versatile design of underwater vehicles could be made since there is no space needed for the man inside the vessel. As the human is removed from the advancing systems, the critical constraints are removed and yet poses the problem of guaranteeing the vehicle's effective capabilities, performing tasks, structure integrity and controlling system including its autonomy.

There are various types of underwater vehicles available today. These submersibles can be classified into few types which are; Human Occupied Vehicle (HOV), Remotely Operated Vehicle (ROV), Autonomous Underwater Vehicle (AUV) and Hybrid Remotely Operated Vehicle (HROV) (Ocean Portal | Smithsonian, 2016) as shown in Figure 1.1. The HOV is a vessel or submarine that carries men or scientists themselves to the deep ocean in order to investigate first-hand the environments and specimens there while ROVs and AUVs are the unmanned craft that let explorers observe and study those places they cannot dive. ROVs are remotely controlled through a cable which connects to the operator on the land or surface platform, limiting their mobility. ROV either in the shape of a submarine or as Remotely Operated Crawler (ROC). New developments in automation led to the creation of AUVs. This type of underwater technology eliminates pilots or operators since the robotic submarines are programmed in advance and do not receive any instruction from the surface.

The latest technology developed is the HROV which is the combination of ROV with AUV, or ROV with ROC. HROV can operate independently with or without a pilot.

As technology continues to advance in the ROV industry, the increasing need for a robust controller becomes apparent. The field of research in focusing one of the types of ROV which a specific discussion on the design and development of the controller for a ROC. Figure 1.1 (e) shows the Remotely Operated Sea Crawler (Project ROSCo) developed at Florida Tech. ROSCo is the new underwater vehicle concept with the ability to take a wide range of underwater excavation project (Florida Tech eCurrent, 2017). The ROC will become the platform of the research on designing an Improved Single Input Fuzzy Logic Controller (SIFLC) for the yaw motion of the vehicle. Previously, the use of underwater crawler is quite unpopular than the submarine type ROV. So, it is important to design and build a ROC that fits into any field. The significance of this study is to target wide area of usage for the ROC such as the ROC can be used in archaeology, seabed monitoring for earthquakes, search and rescue, offshore maintenance and even military purposes. The ROC will be working alongside with other ROV. Both vehicles have their advantages and disadvantages. By working alongside, both vehicles can give more data and sight of a certain situation, for example, SAR operation.

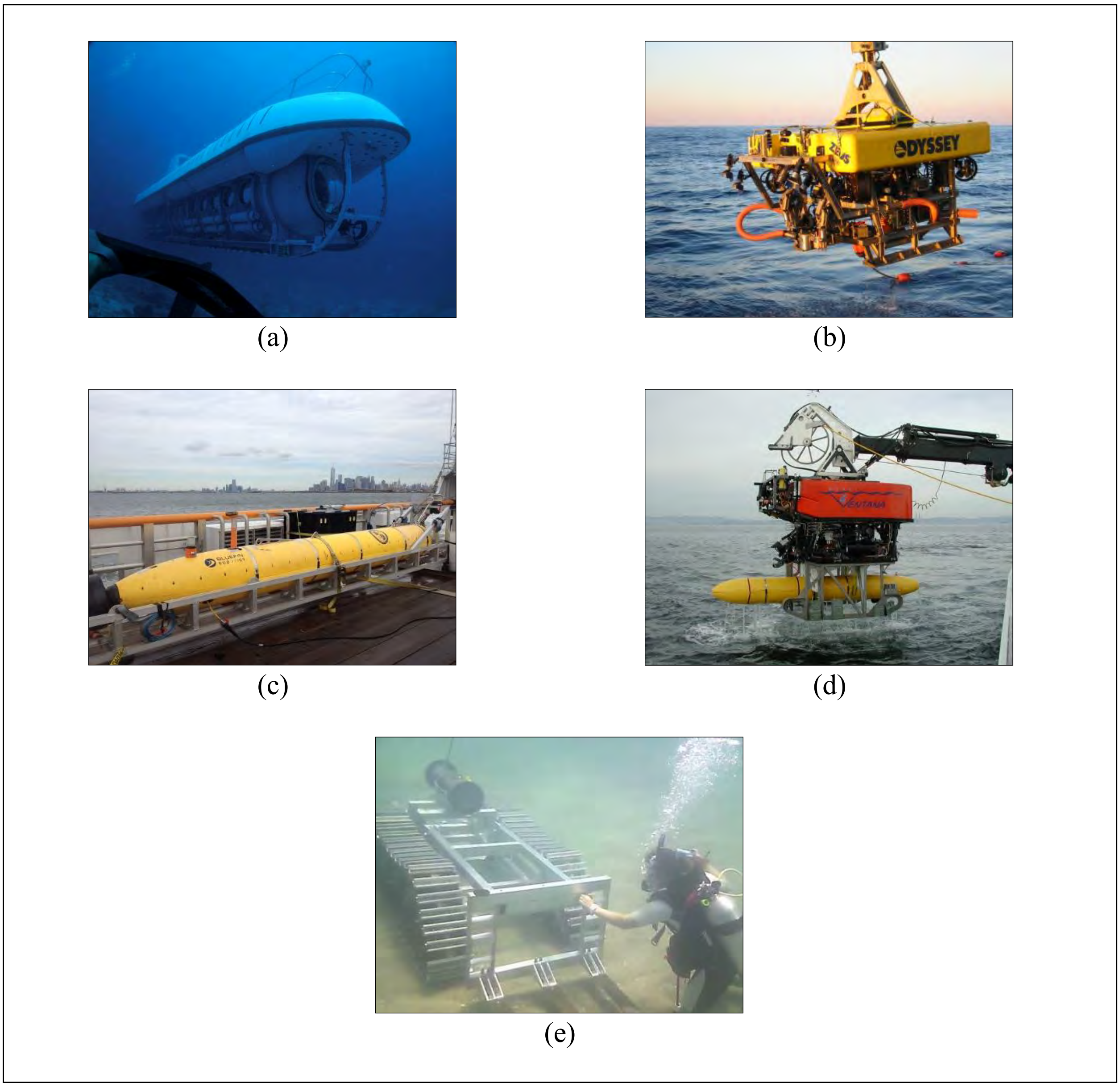


Figure 1.1: Types of Underwater Vehicles. (a) Human Operated Vehicle (HOV) adapted from Atlantis submarines.travel (2017). (b) Remotely Operated Vehicle (ROV) adapted from Shipwrecks: Artifacts & Treasure (2017). (c) Autonomous Underwater Vehicle (AUV) adapted from Exercise, G. (2018). (d) Hybrid Remotely Operated Vehicle (HROV) adapted from MBARI (2017). (e) Underwater Remotely Operated Crawler (ROC) Adapted from Florida Tech eCurrent (2017).

For depth control of the ROV, an existence of overshoot in the system response is highly hazardous. Clearly, an overshoot in the ROV vertical trajectory may cause damages to both the ROV and the inspected structure. Maintaining the position of a small scale ROV within its working area is difficult even for experienced ROV pilots, especially in the presence of underwater currents and waves (Aras and Abdullah, 2015). The operation of ROC also has the same problems in overshoot, rise time and settling time in the control system. Instead of vertical trajectory, ROC is operated on the *x-axis* and *y-axis* which is on the horizontal trajectory torque motors. Thus, this project focuses on controlling the ROC horizontal trajectory as the ROC tries to remain on the desired path and minimize its overshoot, rise time and settling time.

First of all, this project begins by creating an empirical modelling in order to capture the dynamics of the ROC by using system identification technique. From the modelling, an intelligent controller is implemented for yaw control of the ROC based on the Single Input Fuzzy Logic Controller (SIFLC). Later, the Improved SIFLC is designed to adapt the parameters depending on set point. The algorithm is then verified in MATLAB/Simulink platform to test the robustness of the controller' output responses. The results are verified that this technique can effectively control the horizontal path of the ROC with no overshoot including minimizing the settling time and the rise time.

## 1.2 Motivation

In this thesis, there are a few reasons that motivate to carry out the research. The reasons are outlined and justified based on information gathered from previous research on ROV and ROC. These statements explain the factors that affecting the manoeuvrability and navigating the underwater vehicles such as human factors, underwater environment, motion control system and the limitation of those vehicles.